Application of the BigT Burnable Absorber to an OPR1000 Core

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1. Introduction

Burnable absorber is a strong neutron absorber material which transmutes into a less-absorbent material once it captures a neutron. It is used to control excess reactivity and local power peaking, and to optimize fuel utilization. Boron is widely used in Westinghouse-type nuclear reactor designs in the form of the Integral Fuel Burnable Absorber (IFBA)[1]. Gadolinia (Gd_2O_3) is only used in Korea-designed nuclear power plants such as OPR1000 in which Gd_2O_3 of 6~8 w/o is directly admixed with UO_2 fuel with a lower enrichment 0.72~2 w/o. In the case of gadolinia-bearing fuel (GBF), the power distribution in the fuel assembly is seriously distorted, leading to a relatively high 3-D power peaking factor. Also due to the much lower fuel enrichment for the GBF element, the power sharing of the GBF should be much lower and the fuel loading should be limited in comparison with IFBA-type integral burnable absorber. In addition, it is difficult to reduce significantly the critical boron concentration (CBC) further in a GBF-based core since the power peaking and the fuel utilization can be adversely affected.

Very recently a new burnable absorber concept named “Burnable absorber-Integrated control rod Guide Thimble” (BigT) has been proposed for the Pressurized Water Reactor (PWR) [2]. This paper presents a feasibility study of applying BigT to an OPR1000 core as the burnable absorber to replace the conventional Gd_2O_3 integral burnable absorber.

Preliminary lattice calculations based on the PLUS7 fuel assembly installed with the BigT burnable absorber were performed to characterize BigT using metallic Gd as the burnable absorber material. A 3-D OPR1000 core was subsequently modeled with the BigT-installed fuel assemblies and 3-D core depletion analyses were performed to find an equilibrium cycle for a 3-batch fuel management. All neutronic calculations were completed using the continuous energy Monte Carlo SERPENT code [3] with ENDF/B-VII.0 library

2. Methods and Results

2.1 BigT Concept

The BigT burnable absorber needs a small modification in the guide thimble in which its outer or inner surface is slightly modified to make additional space for the insertion of burnable absorber material. It should be noted that the modified guide thimble in BigT still allows movement of control rods. Figures 1 and 2 illustrate two BigT design geometries. Figure 1 shows the so-called pad-type BigT design (BigT type 1) and Fig. 2 shows the AHR (Azimuthal Heterogeneous Ring) type BigT design (BigT type 2).

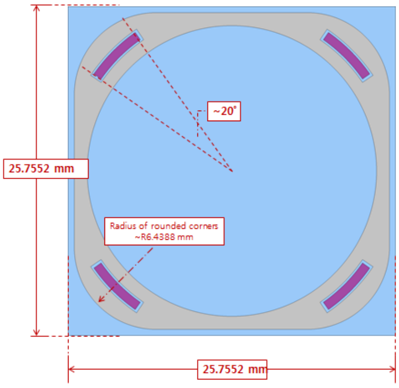

Fig. 1 Pad-type BigT for the PLUS7 fuel assembly

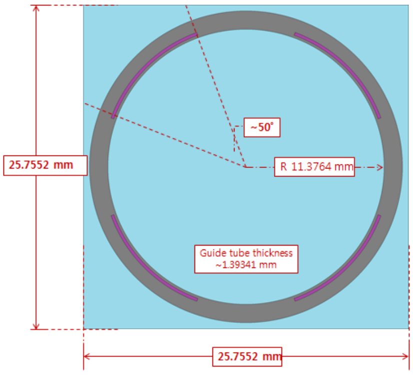

Fig. 2 BigT with AHR for the PLUS7 fuel assembly

It is worthwhile to note that BigT offers flexibility in geometrical shapes allowing the implementation of any possible space filler. For example, rod, pad and ring shaped fillers can be applied between the outer and inner surface of the BigT-equipped guide thimble. The AHR-type burnable absorber can be a homogeneous ring-type BigT, if necessary. This enables a wide variety of designs for different operational specifications.

2.2 Fuel Assembly Design with BigT

In contrast to the GBF, the BigT absorber material is separated from the fuel element. Therefore, depletion characteristics of the BigT-loaded fuel assembly and GBF fuel assembly are quite different. In order to characterize the BigT-loaded fuel assemblies, single lattice calculations were performed to identify the depletion characteristics of a BigT-loaded fuel assembly. Uranium enrichment zoning was used to control the local power peaking in a fuel assembly. Figure 3 shows the enrichment zoning in the fuel assembly. The standard fuel enrichment is 4.5 w/o and 3.8 w/o enrichment is placed in the neighborhood of the big guide thimble and the four corners of the fuel assembly.

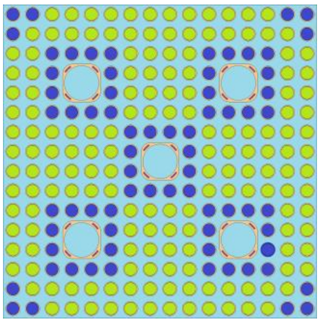

Fig. 3 The layout of BigT-installed PLUS7 fuel assembly (4.5 w/o for green pins, 3.8 w/o for blue pins)

Figure 4 shows the evolution of k-infinity of the BigT-loaded assemblies in comparison with the standard GBF-loaded fuel assemblies and the reference design without any burnable absorbers. The two BigT designs are different in the amount of Gd used. In this study, BigTs for the OPR1000 core were designed such that the CBC of the core can be lower than in the reference actual design. Consequently, as shown in Fig. 4, the reactivity hold-down by BigT is noticeably bigger than in the GBF case. It is noteworthy that the excess reactivity is slightly higher with the BigT burnable absorber than with the GBF case. This is largely for reducing the CBC in the BigT-loaded core.

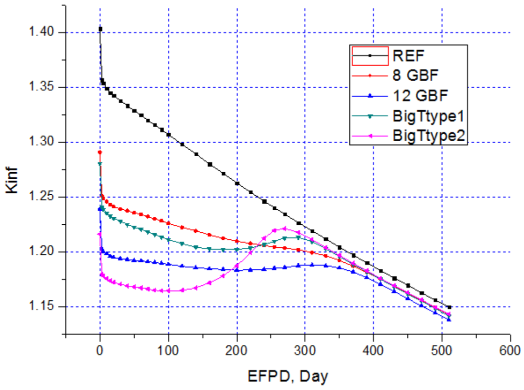

Fig. 4 Lattice reactivity change vs. burnup in BigT-loaded PLUS7 fuel assembly

Since BigT places neutron-absorbing materials around the control rods, there is a valid concern about its impact on reducing the control rod worth and distorting the power distribution. Table 1 shows the results of the control rod worth and power peaking factor of the BigT-loaded fuel assembly in Fig. 4. The reference control rod (CR) worth with GBF was calculated to be about 19,070 pcm for the standard PLUS7 fuel assembly. Table 2 shows the power peaking factors of the conventional GBF-loaded fuel assemblies.

Table 1 CR worth and power peaking in BigT-loaded lattice

Type	CR worth (pcm)	Power Peaking Factor		
		BOC	MOC	EOC
BigT type 1	15,595	1.055	1.067	1.060
BigT type 2	12,528	1.081	1.066	1.065

Table 2 Power peaking factor of GBF fuel assemblies

Type	PF (BOC)	PF (MOC)	PF (EOC)
8 GBF	1.131	1.127	1.115
12 GBF	1.212	1.144	1.104

Table 1 indicates that the CR worth of the BigT-loaded assembly is quite lower than in the GBF-loaded standard design. However, the standard CR design using natural B_4C is adopted in this study since the BigTs are only installed in fresh fuel assemblies and in burned fuel assemblies they hardly affect the CR worth. Nevertheless, it is important to note that the CR worth can be easily increased by using an enriched B_4C for the BigT application, if necessary.

Tables 1 and 2 clearly show that the power peaking of BigT-loaded assemblies are quite lower than in the conventional GBF design.

2.3 OPR1000 Core Analysis with BigT

The BigT technology has been applied to an OPR1000 core, Hanbit Unit 3. Figure 5 shows the fuel assembly loading pattern for a 3-batch fuel management in the OPR1000 core. It should be mentioned that the loading pattern was simply adopted from a related study [4].

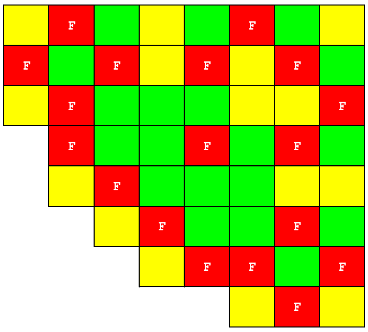

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Fig. 5 Assembly loading pattern of BigT-loaded OPR1000 (fresh=red, once-burned=green, twice-burned=yellow)

The core consists of 64 fresh, 64 once-burned, and 49 twice-burned fuel assemblies. There are 3 types of fresh fuel assemblies, which are different in terms of the burnable absorber loading. Among 64 fresh fuel assemblies (Fas), 16 FAs does not contain any BigTs, while 24 FAs are using type 1 BigT and 24 FAs are using type 2 BigT. As in the actual nuclear design for cycle 6 of Hanbit Unit 3, the cycle length is 470 effective full power day (EFPD) in this work.

An equilibrium cycle of the OPR1000 core was directly searched through repetitive Serpent depletion calculations until convergence for the 3-batch fuel management in Fig. 5 and the resulting reactivity change without soluble boron in coolant and corresponding CBC are plotted as a function of EFPD in Fig. 6 for equilibrium cycle core. Table 3 shows a few important neutronic parameters of the equilibrium cycle for the BigT-loaded core in comparison with the actual nuclear design for Cycle 6 of Hanbit Unit 3. Fig. 7-a, 7-b, and 7-c show the normalized assembly power distributions of the 1/4 core at BOC, MOC, and EOC, respectively.

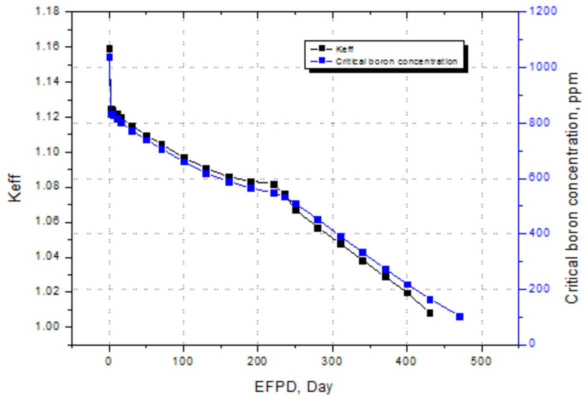

Fig. 6 Change of k-eff without soluble boron and corresponding critical boron concentration in BigT-loaded equilibrium cycle

From Fig. 6, the maximum CBC of the BigT-loaded equilibrium core is only about 1,040 ppm, which is quite lower than the usual CBC of 1300~1500 ppm in actual OPR1000 equilibrium cores. The much lower CBC is due to the much higher reactivity hold-down by BigT at BOC. It is worthwhile to note that the CBC at EOC in Fig. 6 is still quite positive and the core reactivity is still about 800 pcm.

Table. 3 Comparison of neutronic parameters

Item	Reference	BigT-loaded
Cycle length [days]	470	470
Max. CBC [ppm]	1,479	1,039
Total CR worth [pcm]	14,853 (BOC)	15,153 (BOC)
		17,614 (MOC)
		19,093 (EOC)
2-D peaking factor	--	1.53 (BOC)
		1.78 (MOC)
		1.76 (EOC)

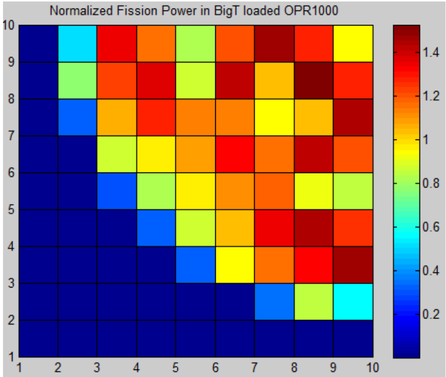

Fig. 7-a Normalized assembly power distribution at BOC

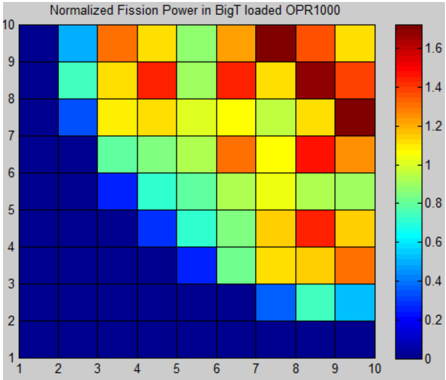

Fig. 7-b Normalized assembly power distribution at MOC

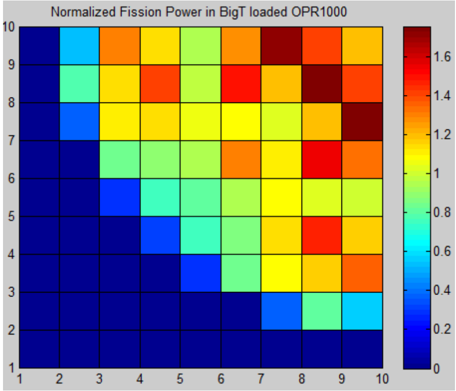

Fig. 7-c Normalized assembly power distribution at EOC

Table 3 indicates that the 2-D power peaking is rather unacceptably high at both MOC and EOC. This is mainly because the loading pattern was not optimized for the BigT-loaded OPR1000 core. It is expected that the peaking factor can be easily reduced by adjusting the assembly loading pattern. It is interesting to note in Table 3 that the total CR worth is 15,153 pcm and comparable to the reference design in spite of the BigT application. It is clear that the total CR worth increases with burnup due to the depletion of BigT burnable absorbers. The high CR worth at BOC is ascribed to the different loading pattern used in this study and the fact that only 48 fresh fuel assemblies are loaded with BigTs. The N-1 CR worth and shutdown margin has not been evaluated yet in this study. However, it is very likely that the equilibrium OPR1000 core with BigTs will provide enough shutdown margin.

3. Conclusions

The neutronic feasibility study of the BigT loaded OPR1000 core has been performed in this work. It has been shown that an 18-month equilibrium cycle can be designed with 64 feed fuel assemblies and the critical boron centration can much lowered in a BigT-loaded OPR1000 core. The power peaking factor of the core was understandably high because the core loading pattern was not optimized yet for the 3-batch fuel management simulation. Nevertheless, it has been demonstrated that the new BigT scheme can replace the traditional gadolinia without any serious compromise in the core performances. It is concluded that the BigT has a very high potential as a promising burnable absorber for the OPR1000 core and it deserves detailed evaluations.

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